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An Economic Analysis of Demand Side Management Considering Interruptible Load and Renewable Energy Integration: A Case Study of Freetown Sierra Leone

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Abstract: Like in most developing countries, meeting the load demand and reduction in transmission grid bottlenecks remains a significant challenge for the power sector in Sierra Leone. In recent years, research attention has shifted to demand response (DR) programs geared towards improving the supply availability and quality of energy markets in developed countries. However, very few studies have discussed the implementation of suitable DR programs for developing countries, especially when utilizing renewable energy (RE) resources. In this paper, using the Freetown's peak load demand data and the price elasticity concept, the interruptible demand response (DR) program has been considered for maximum demand index (MDI) customers. Economic analysis of the energy consumption, customer incentives, benefits, penalties and the impact on the load demand are analyzed, with optimally designed energy management for grid-integrated battery energy storage system (BESS) and photovoltaic (PV)-hybrid system using the genetic algorithm (GA). Five scenarios are considered to confirm the effectiveness and robustness of the proposed scheme. The results show the economic superiority of the proposed DR program's approach for both customers and supplier benefits. Moreover, RE inclusion proved to be a practical approach over the project lifespan, compared to the diesel generation alternative.

Keywords: demand response; interruptible load; price elasticity; renewable energy; photo–voltaic; battery energy storage system

1. Introduction

Achieving the sustainable energy objectives for all (SEforALL) by universal access to modern energy efficiency approach is an essential component for economic development. According to the United Nations Sustainable Development Goal No.7, energy security is pivotal to economic development, access to energy will enable the small-and large-scale business to thrive, and utilities can function efficiently [1,2]. An extensive review of the socio-environmental sustainability benefits of renewable energy (RE) integration, especially for developing economies, is given in [3]. The study identified several opportunities that surround RE incorporation such as improved energy security, better accessibility, climate change mitigation and improved socio-economic development. Access to electricity in Sierra Leone is constrained to a small cross-section of the population, and it is estimated to be less than 15% of approximately 7 million people, with the capital city (Freetown) accounting for a significant proportion of electricity consumption. The energy sector in Sierra Leone is severely challenged with limited generation capacity, ageing, and overloaded transmission and distribution network. Due to the intermittent power supply from the grid, privately owned diesel or petrol generators, which are estimated at a cost of *US*\$300, are often used by companies to supplement the dire needs for electricity supply. However, the running cost at which these companies operate becomes exorbitant, and often their services and products within the country go for higher costs [4,5].

Ref. [6] enlists all generating facilities and their locations across the country with a total state-owned installed capacity of 130 MW. Recently, 50 MW of additional power produced by an IPP (Karpower) was injected into the grid. In [7], a proposed 57 MW thermal plant would be financed by the African Development Bank (AFDB), World Bank and other donor agencies targeted for Freetown electricity demand. At the moment the government has prioritized the improvement of the power industry to carter for the country's energy needs, a cocktail of interventions is being pursued, and this has been backed up with actions such as the budgeted US \$15 million for procurement, restructuring and general overhauling in 2015 [8]. Furthermore, the government has taken credible steps towards improving the current electricity situation across all the stages from generation to distribution. [9] highlights the restructuring of the energy sector in Sierra Leone which has to lead to the decentralization of the National Power Authority (NPA) into separate companies, i.e., the Electricity Distribution and Supply Authority (EDSA) and the Electricity Generation and Transmission Company (EGTC). The restructuring of the energy sector has facilitated competition amongst the IPP into the energy market especially in the capital Freetown, where the load demand is increasing at an exponential rate, and there is a significant deficiency in generation capacity to meet this growing demand especially for the maximum demand index (MDI) and some residential consumers. Despite all these efforts, the Sierra Leone energy sector is still faced with inadequate power generation and weak transmission network; hence, flattening of the load curve in Freetown, through RE integration and consumer participation, has long been acknowledged by the EDSA policymakers as an efficient technique for reducing the electricity production cost. Optimal RE integration is seen as a flexible way of achieving GHG abatement in the planned transition to a carbon-constrained future while meeting the load demand. However, according to [6] achieving both objectives have posed enormous challenges especially for developing countries in that, investing in state-of-the-art RE technologies usually comes with huge initial costs. The authors in [6] have attempted to present a multi-criteria optimal planning approach towards meeting the national net load demand of approximately 700 MW for Sierra Leone in an economic and sustainable manner using different RE technologies, while achieving a significant reduction in GHG emission for the recommended hybrid system (photovoltaic (PV), wind, biomass, battery energy storage system (BESS), Diesel). In [10], the authors proposed the need for optimal sizing of rooftop and ground-mounted grid-connected PV panels and BESS on government buildings in a bid to reduce the supply deficit in the capital, Freetown. However, the authors did not consider demand-side management, through the implementation of demand response (DR) program towards changing the consumers' load demand pattern for improved supply reliability; and the attendant's techno–economic challenges of the existing grid.

In [11], the techno–economic challenges of large-scale RE sources integration considering the security of the existing grid facility and reliability of supply, for weak grids of developing countries, have been succinctly reviewed and analyzed. The problems of RE intermittent output and voltage stability are the key challenges of renewable energy deployment especially for an insufficient grid network. Increase in load demand at a rate not proportionate to the available generation and transmission capacity will compromise system reliability and resiliency. Hence, for intermittent RE generation to augment these problems, optimal energy management schemes are required. In recent years, a popular methodology used to balance supply and demand on the grid, particularly during times of peak load demand, is achieved by changing the demand pattern rather than increasing the supply; this practice is known as "demand response". According to [12], implementation of DR programs can result in shift peak demand, enhance system reliability, reduce transmission bottleneck and highly priced energy bills by shifting or re-adjusting consumption patterns. It can also reduce the effects of intermittent RE generation since the capacity of introduced RE sources will be optimally minimal, and the consumer can also be encouraged to embark on self RE generation and sell self-produced excess energy to the grid. Many authors have carried out research works on effective demand side management (DSM) approach for motivating consumers to modify their demand profile optimally. Researchers have adopted various DSM measures over time; literature [13] gave an extensive analysis of DSM implementations in the industrial sector and highlighted some of the challenges in the implementation of these programs. The authors in [14] presented feasible investment models for energy efficiency and DSM for IPP for various markets and attempted to evaluate the effect of RE penetration on the investment model. A two-level optimization approach DSM was executed utilizing the particle swarm optimization in [15]. The installation cost of the static var compensator, electric vehicle, PV was optimized under the condition that gives the best reactive power incentive to the participating customers towards achieving zero net energy homes. Some of the various DSM measures that have been employed by researchers includes interruptible load agreements; this special tariff is reciprocally advantageous yet, it does not distinctly indicate whether the customer benefit is equivalent to the value they provide to the utility [16]. Execution of DSM programs are yielding promising results in some countries such as in the European Union (EU) [17], Kuwait [18], China [19], South Africa [20], Finland [21] etc. In the United State, DR inclusion in the wholesale markets expanded by roughly 3% from 2016 to 2017, to a sum of 27,541 MW. The contribution of DR to towards meeting the load during peak hours improved from 5.3 % to 5.75.3 % in 2016 [22]. The results obtained indicated that the implementation of DSM proved to be an efficient method in meeting peak load demand without compromising the network stability. The authors in [23] proposed a probabilistic modelling approach that utilizes the available DR during emergencies to reduce ageing of the network's overhead lines and enhance its reliability. In [24], authors proposed interruptible load and capacity market DSM using the Iranian peak load curve as a case study. The results obtained helped the independent system operator (ISO) to distinguish and utilize related DR program which enhances the attributes of the load curve. Related works that attempt to simulate customers' behaviour to different DR programs in a real power network were done. In some of those works, authors investigated the reliability effects of DR programs and reliability indices for generation companies, and transmission network [25]. In [26], the authors proposed a multi-stage residential demand response (RDR) program for the South African system. The RDR was able to contribute to a significant reduction in the energy demand of the peak period.

In this research study, the implementation of DSM and integration of RE into the Freetown distribution network in Sierra Leone to meet the increasing load without compromising the network stability is presented. This research work was carried out in two stages: in phase I, interruptible or curtailable load DR is implemented using price elasticity concept to meet the peak load demand and improving the load profile in the capital (Freetown). In phase II, an introduction of hybridized RE technologies to supply the new load curve after implementation of DR is analyzed through simulation. A genetic algorithm (GA) was used for the optimal sizing of the hybridized renewable energy injection into the generation mix with the decrease in operational and maintenance cost as the objective function, alongside greenhouse gas abatement. The overall importance of this research is to help in providing economic and technical insights to policymakers for the implementation of DSM programs and integration of hybrid RE technologies into the generation mix in the Sierra Leonean capital, city of Freetown.

2. Methodology

2.1. Phase I: Demand Response

The annual drop in the water level at the main Bumbuna Hydro dam which supplies electricity to the capital and some parts of the northern region of the country has forced grid operators and IPP's to issue notices for emergency load shedding and voluntary conservation [27]. This situation is as a result of varying climatic conditions, and the emergency load shedding is usually done within the capital city Freetown for large scale industrial consumers, i.e., MDI and residential consumers in response to the reduction in generation capacity. Insufficient generation capacity results in massive load shedding and constitutes a substantial financial loss to the distribution authority during the dry season. This problem can be mitigated by incorporating the DR mechanism already implemented by other countries reported in the literature. In literature [28], the International Energy Agency (IEA) referred to DSM as "changes that originate from the demand side of the market to achieve large scale energy efficiency improvements by deployment and use of improved technologies and changes in end-user behaviour or energy practices". Also, the 2008–2012 strategic plan was directed towards load-curve modification, and that of 2014–2018 centred on the planning needed to target the investment potential and adequate business models for beneficial market adaptation. These two segments are required for adequate and effective results.

DR can be described as the incentive payments that encourage a temporary reduction in electricity usage in response to a market pricing condition or when system reliability is compromised [29], and it can be grouped in two categories according to their operational mechanism, namely incentive-based and time-based demand response programs. Each of these categories is sub-divided into different programs as shown in Figure 1 below. Time-based rate programs are intended to alter patterns of electricity utilization, including the timing and level of electricity demand. Time-based rate programs include real-time pricing, critical peak pricing, critical peak rebate, variable peak pricing, and time-of-use rates administered through a tariff. Incentive-based demand response programs include direct load control, interruptible, demand bidding/buyback, emergency demand response, capacity market, and ancillary service market programs. Additional details on demand response can be found in [30]. However, this research will centre on introducing interruptible or curtailable load-based DR programs in the Freetown load curve.

2.1.1. Overview of Interruptible Load Model

Customers that sign up to this tariff are subject to curtailment or interruption to reduce utilization to a pre-indicated amount. The curtailed amount of power is based on system reliability constraints in return for an incentive payment or other forms of remuneration in the short term when system stability is being jeopardized due to excessive loading. Some industrial customers can shift or reschedule their demand in the wake of being informed by the utility [16,31]. If customers fail to comply with the contractual provisions, they will be penalized. In this research, the DR programs are generally only available for MDI customers from 12 kW up to 2 MW. It is expected that customers that sign up for this program readjust their demand within 35 min of notification by the utility via the advanced smart metering system. The efficient deployment of this program depends significantly on the infiltration level recorded on the installed smart meters. The frequency of interruptions is usually set based on a strict agreement between the utility and the customers, and it is usually restricted to not more than 100 h per year.

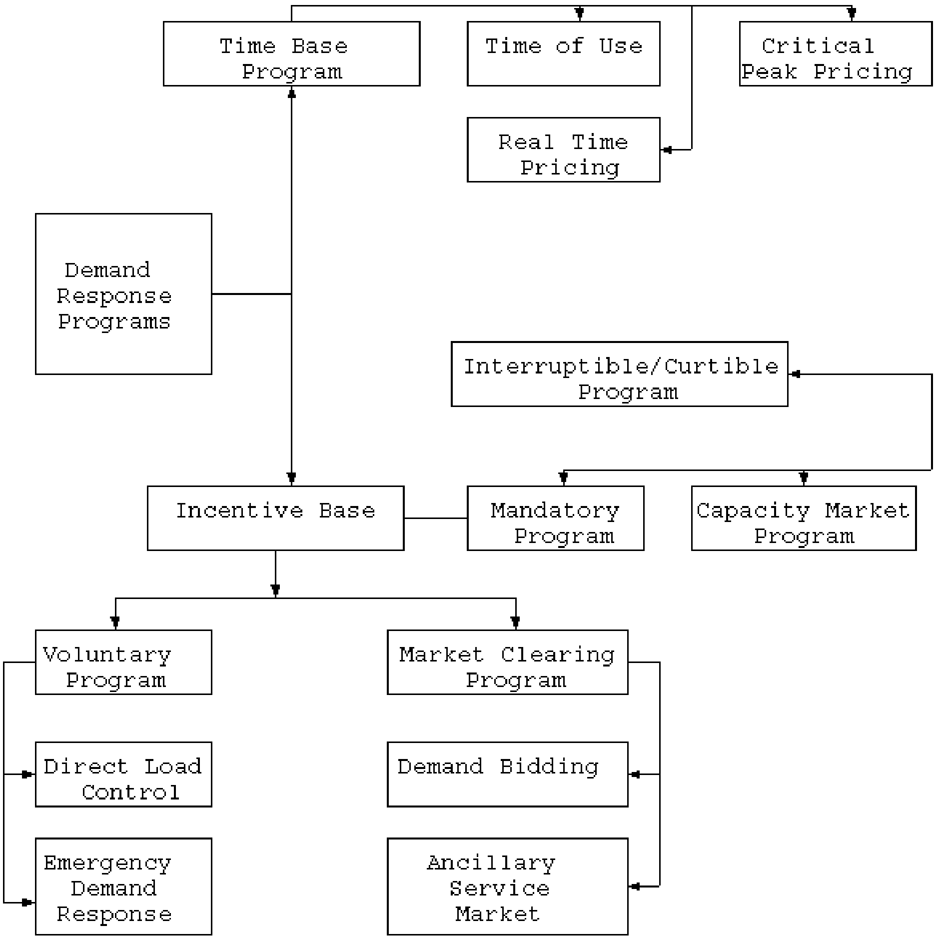

Figure 1. Demand response program categories.

2.1.2. Mathematical Modelling of Interruptible Load DR

In this work, the interruptible DR load model, the impact on the electricity demand prices, the imposed penalties, and the corresponding customer benefits on the Freetown load curve are described as follows:

The typical demand curve in Figure 2 demonstrates that the demand reduces as the price of the commodity rises, i.e., in most cases the rate of utilization of electricity was sensitive to price, which implies that a decrease in electricity price will increase the demand; hence, consumers will be encouraged to raise their demand when the price decreases [24].

$$E = \left(\frac{\partial l}{l} \Big/ \frac{\partial p}{p} \right), \tag{1}$$

where, E is the elasticity coefficient, p = electricity price and l = load demand.

Customarily, a change in the price of one commodity will have impacts on the demand. For example, an increase in the price of electricity in the period i will reduce the demand but may increase the demand in period j if the price of electricity reduces. Negative "self-elasticity" is used to model the first effect, while a positive "cross-elasticity" can be used to model the second case [16];

$$\begin{matrix} E_{ii} = \left(\frac{\partial l}{l} \Big/ \frac{\partial p}{p} \right) \leq 0 \\ E_{ij} = \left(\frac{\partial l}{l} \Big/ \frac{\partial p}{p} \right) \geq 0 \end{matrix}, \tag{2}$$

where E_{ii} is the self-elasticity coefficient, E_{ij} is the cross-elasticity coefficient.

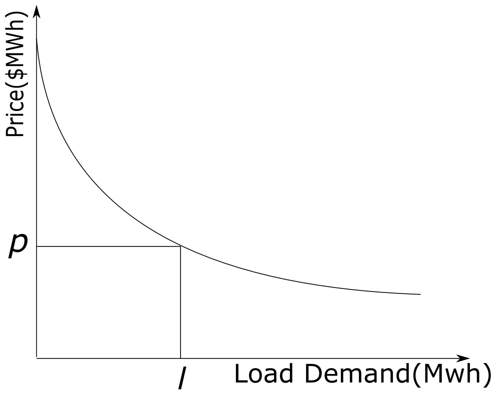

Figure 2. Demand curve.

Proposed Modelling of Single and Multi-period Elastic load

The incentive reward, customer benefits, and penalty are essential motivating factors for the customers to curtail or adjust their initial utilization l_{0i} value to the modified demand l_i at period i, based on the contractual agreement with the utility provider.

$$\triangle l_i = l_i - l_{0i} \tag{3}$$

Hourly incentive revenue for customers participating in this demand response program during the period i is as shown in the equation below.

$$IR(\triangle l_i) = INC_i.(l_i - l_{0i}), \tag{4}$$

where $IR(\triangle l_i)$ is the incentive revenue payment for load reduction ($) and INC is the incentive rate ($/kWh).

In a situation whereby the participating customer fails to oblige to the condition of the contract agreement, the customer has to make the levied penalty payments.

$$X_p(\triangle l_i) = Z_i.(Pi - [l_i - l_{0i}]), \tag{5}$$

where X_p is the levied customer penalty charge ($), Z_i is the penalty rate ($\$/kWh$) and $P(i)$ is DR program level of contract agreement (kWh) during the same period i. In this regard, the customer benefit, Y for period i is as shown below.

$$Y = B(l_i) - l(_i).p(i) + IR(\triangle l(_i) - X_p(\triangle l(_i)) \tag{6}$$

where $B(l_i)$ and $p(i)$ are the customer income ($), and electricity price ($\$/kWh$) in i period respectively. Assuming the consumers choose demand level l_i in other to maximize their benefits after the demand response program then, $\frac{\partial Y}{\partial l_i} = 0$ is equated to zero to maximize the consumer benefit.

$$\frac{\partial Y}{\partial l_i} = \frac{\partial B(l_i)}{\partial l_i} - \rho_o(i) + \frac{\partial IR}{\partial l_i} - \frac{\partial X_p}{\partial l_i} = 0. \tag{7}$$

So,

$$\frac{\partial B(l_i)}{\partial l_i} = p(i) + INC_i + Z_i. \tag{8}$$

The benefit function is a quadratic function as follows;

$$B(li) = B_0(i) + \rho_o(i)[l_i - l_{0i}]\left\{1 + \frac{l_i - l_{0i}}{2E_i.l_{0i}}\right\}, \tag{9}$$

where $B_0(i)$ and $\rho_o(i)$ are the benefit and electricity prices at nominal values respectively. Differentiating Equation (9) and solving for $\frac{\partial B}{\partial l_i}$ then substitute into Equation (8) yields;

$$\rho(i) + INC_i + Z_i = \rho_o(i)(i)\left\{1 + \frac{l_i - l_{0i}}{E_i.l_{0i}}\right\}. \tag{10}$$

Customer utilization will be as shown in the following;

$$l_i = l_{0i}\left\{1 + E_{ii}.\frac{\rho(i) - \rho_o(i) + INC_i + Z_i}{\rho_o(i)}\right\}. \tag{11}$$

In the above equation, l_i and l_{0i} will remain the same if the electricity price does prevail and remain the same without considering the value of the incentive and penalty after implementation of the DR program.

Modelling of Multi-Period of the Interruptible Load Program

In the multi-period, the cross elasticity E_{ij} is calculated for the i-th period with respect to all other periods using the linearity premise given below;

$$\frac{\partial l_i}{\partial p_j}: \text{ constant for i, j = 1,2,3,4.....24.} \tag{12}$$

The linear relationship between price and demand

$$l_i = l_{0i} + \sum_{\substack{i=1 \\ i\neq j}}^{24} E_{ij}.\frac{l_{0i}}{\rho_o(j)}.\{\rho(j) - \rho_o(j)\} \text{ constant for i, j = 1,2,3,4.....24.} \tag{13}$$

It follows that the multi-period comprising incentive and penalty model can be express as shown below;

$$l_i = l_{0i}\left\{1 + \sum_{\substack{i=1 \\ i\neq j}}^{24} E_{ij}\frac{\left[\rho(j) - \rho_o(j) + INC_j + Z_j\right]}{\rho_o(j)}\right\}. \tag{14}$$

Combining Equations (11) and (14) will result in the economic model and the responsive model shown below;

$$l_i = l_{0i}\left\{1 + E_{ii}.\frac{\rho(i) - \rho_o(i) + INC_i + Z_i}{\rho_o(i)} + \sum_{\substack{i=1 \\ i\neq j}}^{24} E_{ij}\frac{\left[\rho(j) - \rho_o(j) + INC_j + Z_j\right]}{\rho_o(j)}\right\}. \tag{15}$$

Equation (15) shows the customer benefit in the 24 h interval when signed up to this program.

2.2. Phase II: Power System Formulation Introduction of Renewable Energy into Demand Response Program

RE technologies, such as solar power and BESS are increasingly becoming an alternative energy source due to their zero emission of greenhouse gases, energy security, availability, etc. PV-panels convert solar irradiance into electrical power; the installation can be standalone or grid-connected. Due to the intermittent nature of solar radiation, the PV is usually connected with a BESS system to offset the intermittent nature of the solar power, i.e., hybrid connection of PV and BESS. The authors in [32] presented hybridized RE source–thermal generation model was presented for the Northern Cyprus Turkish Republic. The study suggests an enhancement in a hybrid RE-thermal power system execution by predicting reliable outputs that can fuse RE technologies to the conventional power source.

In this research, the DSM approach is employed when the existing diesel generating units in the network cannot meet the required load demand, after the interruptible or shifting DR program has been executed and the RE technology has been introduced. Energy from the solar generators or grid power may be stored when there is excess generated PV power or when the cost of electricity from the grid is economical. The stored energy can be controlled for economical usage in future when the electricity demand is high during load peak times, or when there is unavailable PV power. It is worthy to note that RE sources are being utilized in the valley and low peak periods. Figure 3 shows the system configuration and the flowchart, of the complete design process of two-stage DR program using RE sources, are presented in Figure 4 below.

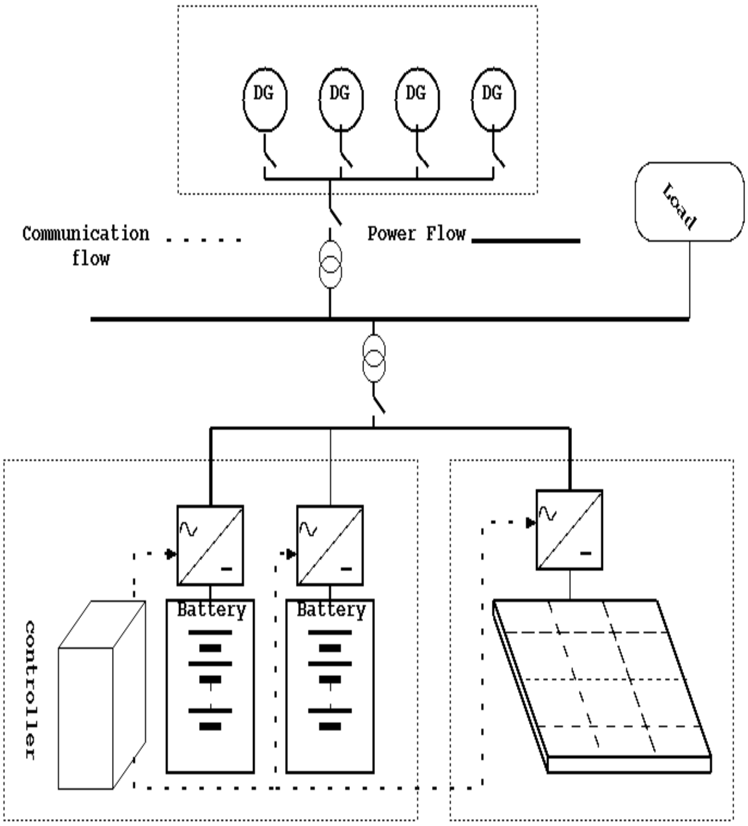

Figure 3. The proposed system model.

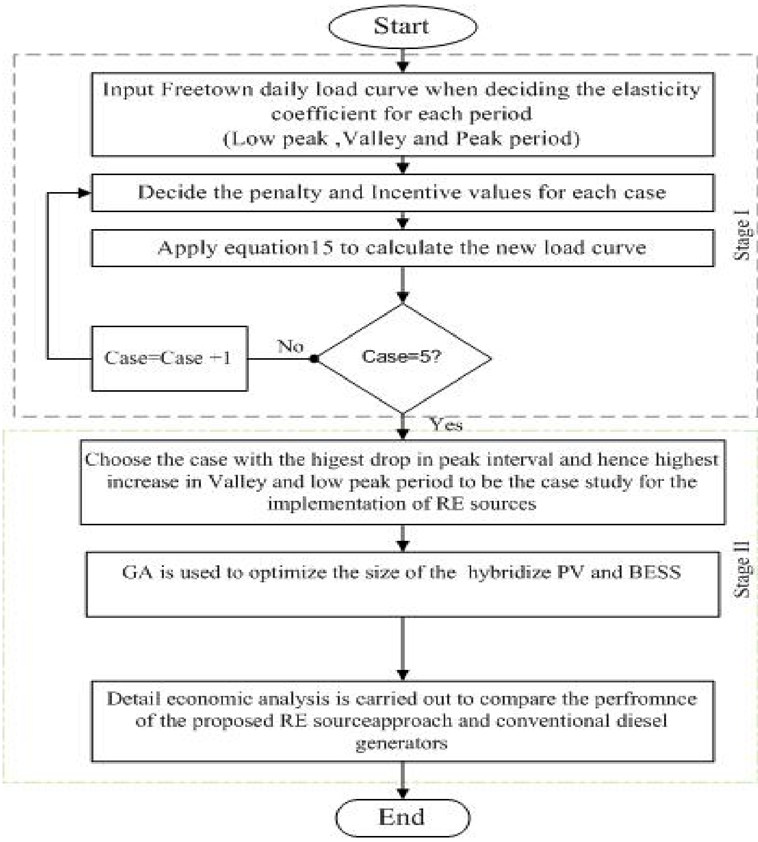

Figure 4. Flowchart of the proposed model.

The parameters used in the system formulation are given in Table 1.

Table 1. Variables used in this research.

VARIABLE	NOMENCLATURE	VALUE
Interest rate	i	0.1
Index year	e (years)	
Inflation rate	σ	0.04
Escalation rate	$\mu_{pv} = \mu_{Bat}$	0.075
Inverter efficiency	η_{inv}	0.9
PV Initial cost	τ_{PV} (\$/m^2)	251
Total Area of PV	X_{pv} (m^2)	
Annual O&M Cost of PV	OM_{pv} (\$/m^2/yr)	$0.01 \times X_{pv}$
The replacement cost of PV	R_{cpv} (\$)	0
Resale price of PV	S_{rpv}	$0.25 \times \tau_{PV}$
PV efficiency	η_{pv}	0.14
The capital Investment cost of PV	V_{pv} (\$)	
Battery charging efficiency	η_{bat}	0.9
Battery discharging efficiency	η_{dis}	0.9
Number of Batteries	Z_{bat}	
Battery cost	Q_{bat} (\$/MW)	200,000
Battery replacement cost	R_{cbat}(\$)	
Hourly self discharge	γ	0
Battery Capacity		50 kW

2.2.1. The Output of PV Array

The output power supplied by the PV panel during the period i in the valley and low peak period is presented in the equation below;

$$PV_{out} = \eta_{PV}.X_{PV}.H(i), \tag{16}$$

where PV_{out} is the PV output power, η_{PV} efficiency of the PV panels, X_{PV} is the total area occupied by the panels in m^2 and $H(i)$ is the solar radiation in period i in kW/m^2.

2.2.2. Battery Energy Storage System(Bess)

The aggregated power from the thermal unit P_{th} and PV panel in period i is as shown below;

$$P_T(i) = P_{pv}(i) + P_{th}(i), \tag{17}$$

where P_T is the sum of the generated power.

From Equation (17) above, if the total generated power cannot meet the load demand l at any period i, it indicates that the state of charge (SoC) of the battery at the period i with inverter efficiency η_{inv} is:

$$P_T(i) \geq \frac{l(i)}{\eta_{inv}}. \tag{18}$$

At any given period i when there is an excess generation from the thermal and PV, BESS can be charged. The state of charge can be calculated as shown below [33];

$$SoC(i) = SoC(i-1).(1-\gamma) + \left(P_T(i) - \frac{l(i)}{\eta_{inv}}\right)\eta_{bat} \tag{19}$$

The storage state of charge, $SoCs(i)$, at the end of the period i, as a function of its state of charge at the previous period of the charging or discharging that took place during the period i.

Where $SoC(i)$ is the state of charge, γ is the self-hourly discharge rate and η_{bat} battery charging efficiency.

$$SoC(i) \leq SoC^{max}, \tag{20}$$

where SoC_{max} is 80% of the total capacity of the battery bank. In cases wherein $P_T(i) \leq \frac{l(i)}{\eta_{inv}}$, then there is insufficient generation capacity from i.e., PV and thermal, the load demand will be met by the battery energy storage system. During the discharging period, the SoC is as follows;

$$SOC(i) = SOC(i-1).(1-\gamma) + \frac{\left(\frac{l(i)}{\eta_{inv}} - P_T\right)}{\eta_{dis}}, \tag{21}$$

where η_{dis} is the efficiency of discharge of the battery

The state of charge should not be less the minimum SoC_{min}

$$SoC(i) \geq SoC_{min}. \tag{22}$$

Therefore the minimum state of charge is 20% of the total capacity of the battery bank.

3. Case Study and Results of the Simulation

In order to evaluate the effect of interruptible or curtailable DR, the proposed approach is employed to Freetown network load demand using December 2017 data, as shown in Figure 5. The average electricity price negotiated by EGTC, EDSA and the Ministry of Energy (MoE) in 2017 was 0.178 $/kWh, [34,35]. The daily load curve is divided depending on the nature of demand into three intervals: Low peak (00:00–7:00), valley (8:00–14:00) and peak load (15:00–22:00); and DR program will be employed to decrease the demand in peak load periods. Data was acquired through desk research, key informant interviews, sector policymakers and discussions with senior engineers at EDSA and EGTC. In this research, implementation of this program is 10% modification of the total load of the participating customers and its incumbent for customers who signed up to this program to shed 10% of their load when being notified as in the agreed contract. The incentive and penalty values designated for customers who signed up for this program and the price elasticity values are shown in Tables 2 and 3 respectively [36].

Table 2. Incentives and penalties values.

CASE	INCENTIVE $/kWh	PENALTY $/kWh
1	0	0
2	0.178	0
3	0.089	0.089
4	0.029	0.059
5	0.178	0.178

Table 3. Self and cross elasticity for various periods.

Period	Low Peak (00:00–7:00)	Valley (8:00–14:00)	Peak Load (15:00–22:00)
Low Peak (00:00–7:00)	−0.1	0.01	0.012
Valley (8:00–14:00)	0.01	−0.1	0.016
Peak Load (15:00–22:00)	0.012	0.016	−0.1

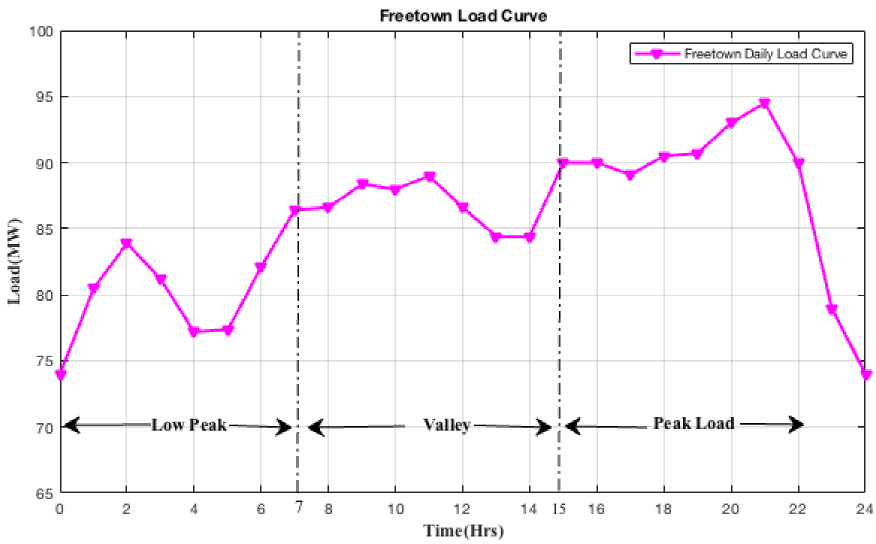

Figure 5. Freetown demand curve.

3.1. Results of Dr Program Execution and Analysis (Phase I)

1. Case 1 In case I, the peak load curve was considered without the execution of the proposed DR program. As shown in Table 4, the peak load was 94.5 MW, energy consumption was 2057 MWh, customer bill was $366,130, peak to valley distance was 21 MW. These four indices improved after implementation of the proposed DR model, as subsequently explained in the following subsections.
2. Case 2 As shown in Table 4, penalty and incentives are taken as 0.178 $/kWh and 0 $/kWh respectively. Comparing the results with the base case, net reductions were observed on the following; peak load, by 4.3% (90.42 MW), energy consumption by 2.2% (2012 MWh), customer bill by (2.2%) $35,160 and peak to valley reduction by 23.8% (16 MW) as shown in Figure 6. Also,

the customer benefit increased to $18,813 and supplier benefits reduced by 5.1% ($18,820) as compared to the base case.

3. Case 3 In this case, the incentive and penalty are both at the equivalent value of 0.089 $/kWh as observed in Figure 6 which also depicts similar profile characteristic as in case 2 with decrease customers bill by 2.18% ($7970), 4.12% (90.42 MW) of peak load reduction. Also, supplier revenue decreased by 3.13% ($11470) as compared to the base case scenario. The incentive payment in case 2 doubled as in case 3, which is legitimized by Equation (15).
4. Case 4 From Table 4, taking penalty and incentives as 0.029 $/kWh and 0.059 $/kWh respectively and comparing the results obtained to that of the case 1, it can be observed that there is net reduction in the following: peak load by 3.5%(91 MW), energy consumption by 1.06% (2035 MWh), and customer bill by 1.1% ($362,190) and peak to valley reduction by 19% (17 MW) as shown in Figure 6.
5. Case 5 In this case, given the incentive and penalty values as 0.0178 $/kWh. From the simulation and comparing with the results obtained in case I, it observed that there is a net reduction in energy consumption by 4.35% (1967.40 MWh), customer bill by 4.32% ($350,200) and peak load by 2.80% (91.85 MW) as shown in Figure 6. Also, an increase in supplier revenue, customer benefit was observed from the simulation as shown in Table 4.

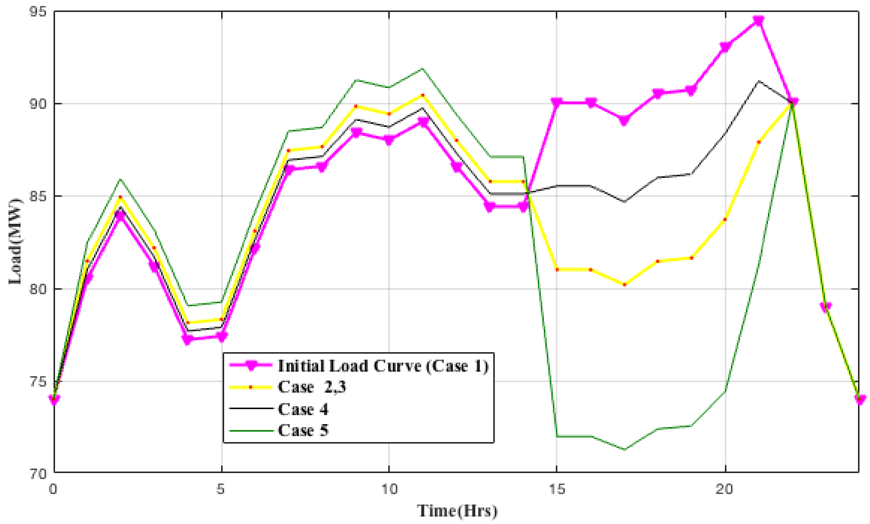

Figure 6. Impact of demand response for different scenarios.

Table 4. Analysis and load profile characteristics.

PARAMETERS	CASE-1 (Base)	CASE-2	CASE-3	CASE-4	CASE-5
	Incentive = 0.0 Penalty = 0.0	Incentive = 0.178 Penalty = 0	Incentive = 0.089 Penalty = 0.089	Incentive = 0.029 Penalty = 0.059	Incentive = 0.178 Penalty = 0.178
Energy Consumption (MWh)	2056.90	2012.20	2012.20	2034.80	1967.40
Customer Bill ($)	366,130.00	358,160.00	358,160.00	362,190.00	350,200.00
Peak Load (MW)	94.50	90.42	90.42	91.22	91.85
Load Factor (%)	90.69	92.72	92.72	92.93	89.25
Incentive ($)	0.00	10,848.00	5424.10	873.77	21,696.00
Penalty ($)	0.00	0.00	1924.70	3054.70	3585.00
Customer Benefit ($)	0.00	18,813.00	13,137.00	3826.30	37,627.00
Supplier Revenue ($)	366,130.00	347,310.00	354,660.00	364,370.00	332,090.00
Energy reduction (%)	0	2.22	2.22	1.09	4.55
Peak Reduction (%)	0	4.31	4.31	3.46	2.81
Peak to Valley (MW)	20.50	16.42	16.42	17.23	20.57

3.2. Results of the Introduction of Renewable Energy (Phase II)

Figure 7 shows the introduction of RE technologies into the generation mix after the execution of the demand response program. The proposed model is evaluated using a genetic algorithm (GA). GA is a method to solve both constrained and unconstrained optimization problems that are based on natural selection. A key step in GA applications is the definition of the objective (fitness) function which is the function to optimize. In this case, the fitness functions are the summation of the net mismatch between the generation and the load, i.e., for low peak, Valley, and peak load hours. The fitness function (F_x) is shown in equation (23). The obtained best fitness is as presented in Figure 8

$$F_x = \sum_{i=1}^{N} | \{gen - load\} | . \quad (23)$$

In this research, PV and BESS are considered to offset the deficiency in the existing generation capacity from the thermal units in peak and valley periods, especially during the dry season, when the main hydro supplying electricity to the Capital, is reduced to more than half of its designed capacity. Table 5 shows the solar irradiance [37]. Case 5 was selected for the penetration of PV and BESS due to the highest drop in peak period henceforth highest increase in the valley and low peak period occurred in this case. It represents the largest gap and should be filled in valley and peak interval and from the simulation results shown in Figure 7, it is observed that, between the hours 00:00–10:00 h, where we have limited solar radiation, the battery can be seen discharging it stored energy covering the shortfall for the PV power. From 11:00–17:00 h, we observed an increase in solar irradiance. During this period the PV will be providing power supply while the battery is charging. The state of charge and discharge is as shown in Figure 7.

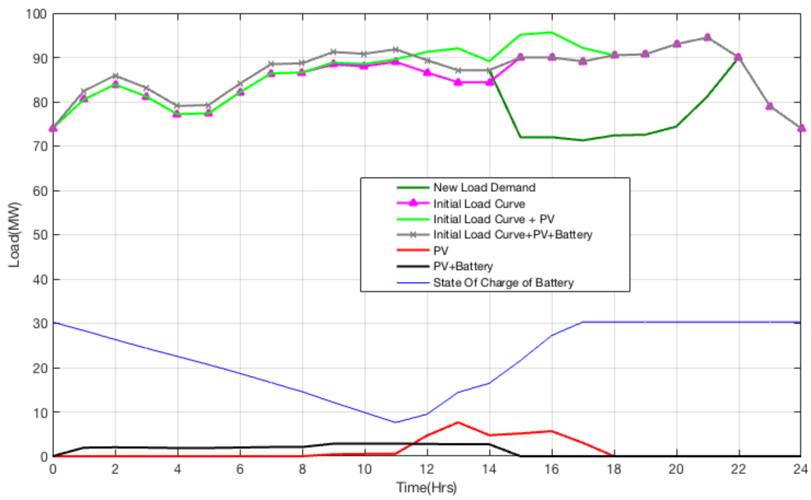

Figure 7. Introduction of renewable energy.

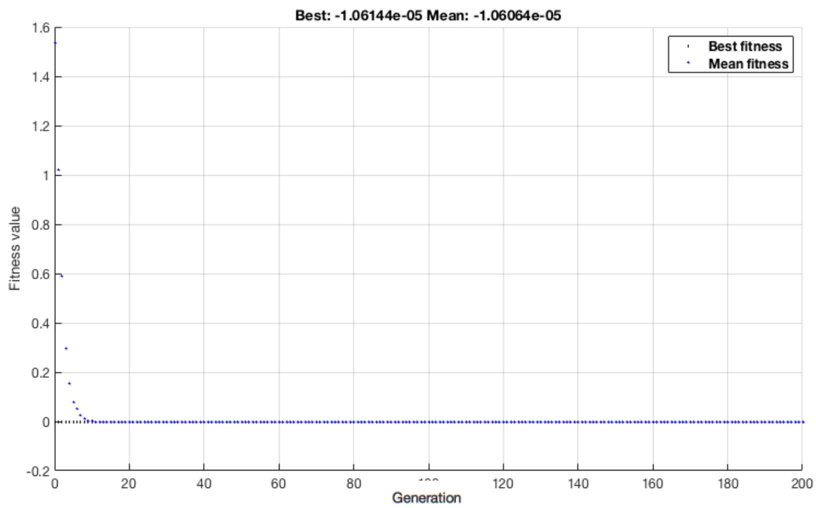

Figure 8. Fitness function.

Table 5. Solar irradiance.

Time	Solar Radiation w/m^2	Time	Solar Radiation w/m^2
0:00	0	12:00	531
1:00	0	13:00	873
2:00	0	14:00	543
3:00	0	15:00	587
4:00	0	16:00	646
5:00	0	17:00	347
6:00	0	18:00	0
7:00	0	19:00	0
8:00	0	20:00	0
9:00	50	21:00	0
10:00	60	22:00	0
11:00	66	23:00	0

In order to investigate the robustness and effectiveness of the proposed control scheme from the economic point of view, the annual cost of implementing RE projects are compared with the conventional diesel generators suppliers.

3.2.1. Cost Analysis

The cost analysis is used to measure the economic performance of the deployed DR program considered for the system under study. For a project life of 20 years, the main costs considered were the capital cost of investment, cost of operation, maintenance cost and resale cost of salvageable components. The battery was replaceable after every five years throughout the project life, and this was considered in the cost analysis.

1. PV system cost The capital investment cost over 20 years period of operation is as shown below, and parameters used in the cost analysis are given in Table 1;

$$V_{pv} = \tau_{PV} \times X_{pv}, \tag{24}$$

where τ_{PV}, X_{pv} are the initial investment cost and the total area of the PV respectively. The total operational and maintenance cost (OM_{cpv}) of PV is as shown below, where μ_{pv} denotes the escalation rate for 20 years operational period.

$$OM_{pv} = \tau_{pv} \times X_{pv} \times \left[\left(\frac{1+\mu_{pv}}{1+i} \right)^{e} \right] \tag{25}$$

$$OM_{cpv} = \sum_{e=1}^{20} \left(OM_{pv} \right).$$

The PV replacement (R_{cpv}) cost is considered zero, therefore the total resale price after the 20 years period is as shown;

$$S_{rpv} = s_{pv} \times X_{pv} \times \left[\left(\frac{1+\sigma_{pv}}{1+i} \right)^{20} \right] \tag{26}$$

It follows that the total cost of PV X_n over 20 years is

$$X_n = V_{pv+OM_{CPV}-S_{rpv}}. \tag{27}$$

2. Battery cost In this research, the project lifetime was 20 years and the lifetime of the battery was five years, it follows that the battery should be replaced three times during the project life cycle. The capital investment cost of the battery for five years is as shown below;

$$Batt_c = Z_{bat} \times Q_{bat}. \tag{28}$$

Replacement cost after period j is given by

$$R_{cbat} = Z_{bat} \times Q_{bat} \times \left[\left(\frac{1 + \mu_{Bat}}{1 + i} \right)^e \right]. \tag{29}$$

Total replacement for 20 years period

$$R_{cbat} = Z_{bat} \times Q_{bat} \times \sum_{e=5,10,15} \left[\left(\frac{1 + \mu_{Bat}}{1 + i} \right)^e \right]. \tag{30}$$

For diesel generators, the maintenance cost of 0.0075$ kWh is considered [38]. Moreover, depending on the Freetown load curve, diesel generators will operate approximately 14 h daily in this scheme (Valley to Off-Peak hours), that will give about 5110 h of annual operation. As the statistics recommend replacement of the diesel generator after overuse of 20,000 operating hours, the conventional generators are replaced after every four years, and 1.25 $million/MW [38] is considered as the replacement cost. Figure 9 shown below validates the superiority of the proposed model of RE sources inclusion to cover all its life cycle cost only after 12 years from the lifetime of the proposed project and the remaining eight years will be considered profit for the supplier. Moreover, the environmental effects of conventional diesel generators will be decreased significantly by applying this approach, and this can be an additional gain for utilizing the proposed methodology.

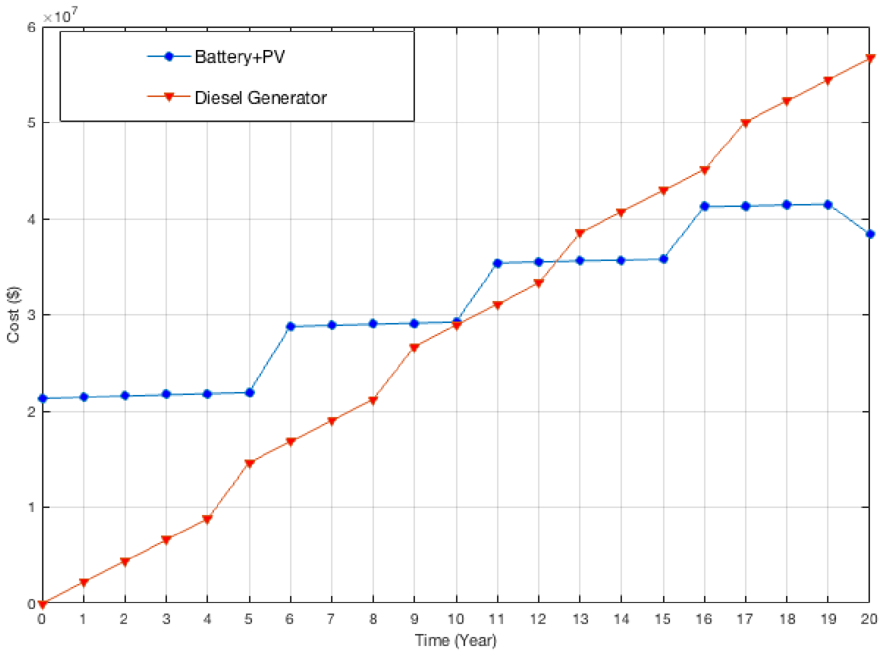

Figure 9. Cost comparison of renewable energy (RE) and diesel generators.

4. Results Discussion

In this research, formulation of DR program for the electric power system of Sierra Leone, considering Freetown (capital city) load curve was investigated. The research was divided into two implementation phases which mainly concentrated on the economic benefits of the consumers and suppliers.

- In phase I, the proposed control scheme was applied to the Freetown distribution network. Five case studies were considered with different incentive and penalty values. The results obtained from the simulation validate the efficiency of the proposed DR control approach to maximize customer profit by decreasing the customer bills and also increasing customer benefits. Furthermore, from the supplier point of view, the proposed methodology succeeded in decreasing the peak load, and reduced the energy consumption; in addition to mitigating the load factor that significantly enhances the power of the power system.
- In phase II; PV and BESS are introduced as RE-sources to meet the variance in load in the valley and Off-peak periods, hence, decreasing the use of conventional diesel generators. This step will lead to a decrease of GHG emissions which has harmful effects on the environment.
- The cost-benefit analysis was implemented to investigate and compare the economic effects of RE sources inclusion to that of convention diesel generators. The results confirm the ability of RE sources to cover the lifecycle cost of the project after twelve years. Depending on these results, the supplier can gain eight years of profit due to the RE energy sources inclusion in addition to its non-hazardous effect on the environment.

5. Conclusions

A novel two-stage DR program using RE sources has been executed in this paper. In the first stage, interruptible or curtailable DR program was employed with the daily load curve of Freetown, Sierra Leone's capital city, to shift the customer demand from the peak load periods to the valley and low peak periods. Additionally, the PV and BESS are utilized to meet the increasing demand in the valley and low peak periods after implementation of the DR program. The GA is used to optimize the size of PV and BESS. Five scenarios are implemented to confirm the effect and robustness of the proposed DR model to decrease peak load and increase load factor and customer benefits.

Moreover, a detailed cost analysis is held to investigate the superiority of the proposed RE inclusion approach to decrease the total cycle cost compared to that of diesel generators. The performance of the system is enhanced significantly by using the proposed two-stage control methodology. Simulation results show the ability of the proposed DR programs to decrease the customer bill, reduce peak load, mitigate load factor and also increase customer benefits. Furthermore, simulations clarify that RE sources inclusion approach will cover its lifecycle cost after 12 years from the total lifetime of the project, which means that at least eight years of profit for the supplier in addition to a significant reduction of environmental of conventional generators.

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Nomenclature

MDI	maximum demand index
DR	demand response
BESS	battery energy storage
GHG	green house gas
DSM	demand side management
IEA	international energy agency
NPA	national power authority

EDSA	electricity distribution and supply authority
EGTC	electricity generation and transmission company
AfDB	Africa Development Bank
ISO	independent system operator
RDR	residential demand response
$E_{i,j}$	cross elasticity
$E_{i,i}$	self elasticity
l_{oi}	initial load.
l_i	modified demand
i	i-th period
j	j-th period
INC_i	incentive rate
$B_o(i)$	benefit at nominal value
Z_i	penalty rate
$\rho_o(i)$	electricity price at nominal value
Y	customer benefit
PV_out	output power of PV
GA	genetic algorithm
IPP	independent power producers
PV	photovoltaic
RE	renewable energy
EU	European Union
E	elasticity
$\rho(i)$	electricity price
l	load demand
$P(i)$	DR program contract
$B(l_i)$	customer income in period i-th
$IR(\triangle l_i)$	Incentive revenue payment
$X_p(\triangle l_i)$	levied customer penalty
η_{pv}	the efficiency of PV panel
X_{pv}	the area occupied by the PV-panel
H_i	solar radiation
P_T	Sum of aggregated power
$P_{PV}(i)$	PV power in i-th period
P_{th}	aggregated power of thermal units
SoC	state of charge of battery
η_{inv}	inverter efficiency
γ	hourly discharge rate
η_{bat}	battery charging efficiency
C_{bat}	nominal capacity of the battery bank
η_{dis}	battery discharging efficiency
SoC_{min}	minimum state of charge of the battery
SoC^{max}	maximum state of charge of the battery
e	index year
V_{pv}	capital investment cost
τ_{pv}	initial investment cost of PV
OM_{pv}	annual operational and maintenance cost of PV
μ_{pv}	escalation rate
R_{cpv}	the replacement cost of PV
$_{pv}$	resale cost of PV
σ_{pv}	the inflation rate of PV
X_n	total cost of PV over 20 years
$Batt_c$	capital cost of battery
Z_{bat}	total number of battery
Q_n	battery cost

R_{cbat} the replacement cost of battery
μ_{bat} escalation rate of battery

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